VARIABLE OPTICAL ATTENUATOR HAVING A WAVEGUIDE AND AN OPTICALLY COUPLED LAYER WITH A POWER MONITOR

FIELD OF THE INVENTION

[0001] The present invention relates generally to optical communications device technology, and more particularly, to variable optical attenuators formed on electro-optical materials.

BACKGROUND OF THE INVENTION

[0002] High-speed optical networks transmit information long distances as light signals through optical fiber networks. Amplification of optical signals, preferably using optical amplifiers, is required at regular intervals along a long distance network to maintain signal strength. Since some advanced networking techniques transmit many channels simultaneously through the same fiber, it is important that the gain is the same for each channel. For example, networks that use wavelength division multiplexing (WDM) transmit many channels over the same fiber, with each channel at a different wavelength. Since current optical amplifiers have wavelength dependent gains, repeated amplification can distort the information being transmitted. Wavelength-dependent gain can be overcome by optical equalization of the different signal channels. In practice, this equalization is performed by use of a variable optical attenuator (VOA).

[0003] There are several types of VOAs currently available. In one type of VOA, a Mach-Zehnder interferometer has a material in the optical path having a temperature dependent refractive index (the "thermo-optic effect"). The interferometer is configured such that a change in the temperature of the thermo-optic material results in a change in the output light intensity. Attenuation is thus adjusted by control of the temperature of the thermo-optic material. Although thermo-optic VOAs have good optical coupling properties and are polarization independent, they suffer from high power usage and a relatively slow response time of greater than 10 ms, and thus they are not appropriate for high speed networking.

[0004] Another currently available VOA employs micro-electro-mechanical system (MEMS) elements, in which movable, micro-elements are used to attenuate light. MEMS devices are also relatively slow, with response times on the order of milliseconds, and have reliability issues resulting from the many moving parts of the VOA.

[0005] In addition to speed and reliability, there is also a need to have VOAs that can be

assembled into arrays or into other devices. For the large number of channels envisioned for WDM networks, it would be a great advantage to be able to fabricate VOAs of smaller size, to assemble VOAs into arrays, and to incorporate them into other WDM devices, such as multiplexers or demultiplexers. Heretofore, it has been difficult to configure VOAs into arrays or within other devices.

[0006] Therefore, it would be desirable to have a VOA that is faster than currently available devices, and that can be assembled in large numbers as an array. It is also desirable to have a VOA that is manufactured by techniques that allow for integration into other WDM devices.

SUMMARY OF THE INVENTION

[0007] The present invention solves the above-identified problems with VOAs by providing waveguides having attenuation that is controlled by application of an electric field to an electro-optical material that is part of the waveguide or is adjacent to a cladding of the waveguide.

[0008] It is one aspect of the present invention to provide a device for variably attenuating an optical signal having a waveguide and a layer, each with a first refractive index, separated by a cladding of variable refractive index. A portion of the cladding between the waveguide and layer includes an EO material and electrodes that provide an electric field for varying the refractive index of the EO material according to the voltage difference between the electrodes. In one embodiment, the cladding and EO material have a second refractive index in the absence of an electric field, resulting in a low-loss waveguide. The EO material can be changed to have the first refractive index by the application of a voltage difference, resulting in a high-loss waveguide, where a large portion of the light is coupled into the layer and thereby attenuated. A sensor optically coupled to the layer provides an indication of the amount of light removed from the attenuated signal that can be used to control the voltage applied to the electrodes. In another embodiment, the invention comprises an array of individual devices for variably attenuating individual ones of a plurality of optical signals.

[0009] It is another aspect of the present invention to provide a device for variably attenuating an optical signal. The device includes a waveguide having a core with a first refractive index and a cladding comprising a material with a second refractive index and an EO material having a first side adjacent to the core and a second side distal from the core. The device also includes a pair

of electrodes to produce an electric field within the EO material and change the refractive index of said EO material, and a layer adjacent to the second side of the EO material and having a refractive index approximately equal to the first refractive index. The amount of incident waveguide light transmitted through said waveguide varies with the voltage applied to the pair of electrodes, with at least a portion of incident light not transmitted through said waveguide being transmitted along said layer. It is preferred that the refractive index of the EO material varies with the applied voltage difference from the first refractive index to the second refractive index. In one embodiment, a sensor is optically coupled to the layer to produce an output proportional to the light in the layer. It is preferred that a controller receives the sensor output and controls a voltage difference to the electrodes. In another embodiment, the first material is on a substrate. One of the pair of electrodes is between the substrate and first material, and the other of the pair of electrodes is on the layer distal to the core. In yet another embodiment, each of the pair of electrodes are coplanar and parallel with the waveguide, each of the pair of electrodes has an edge, the pair of edges has a spacing, and at least a portion of the EO material is between the pair of edges. The spacing may be either constant or can be regularly repeated along the waveguide.

[0010] It is yet another aspect of the present invention to provide an array of devices for variably attenuating a plurality of optical signal. The array includes a plurality of spaced waveguides. Each waveguide has a core with a first refractive index and a cladding comprising a material with a second refractive index and an EO material having a first side adjacent to the core and a second side distal from the core. The device also includes a pair of electrodes to produce an electric field within the EO material and change the refractive index of said EO material, and a layer adjacent to the second side of the EO material and having a refractive index approximately equal to the first refractive index. The amount of incident waveguide light transmitted through said waveguide varies with the voltage applied to the pair of electrodes, with at least a portion of incident light not transmitted through said waveguide being transmitted along said layer. It is preferred that the refractive index of the EO material varies with the applied voltage difference from the first refractive index to the second refractive index. In one embodiment, a sensor is optically coupled to the layer to produce an output proportional to the light in the layer. It is preferred that a controller receives the sensor output and controls a voltage difference to the electrodes. In another embodiment, the first material is on a substrate. One of the pair of electrodes is between the substrate and first material, and the other of the pair of electrodes is on

the layer distal to the core. In yet another embodiment, each of the pair of electrodes are coplanar and parallel with the waveguide, each of the pair of electrodes has an edge, the pair of edges has a spacing, and at least a portion of the EO material is between the pair of edges. The spacing may be either constant or can be regularly repeated along the waveguide.

[0011] In a further aspect of the present invention, an array of variable optical attenuators is provided that is more reliable and less expensive than those of the prior art.

BRIEF DESCRIPTION OF THE DRAWINGS

[0012] The foregoing aspects and the attendant advantages of this invention will become more readily apparent by reference to the following detailed description when taken in conjunction with the accompanying drawings wherein:

[0013] FIG. 1 is a schematic of an array of VOAs and corresponding power meters of the present invention as used in a gain equalizer of a WDM network;

[0014] FIG. 2 is a top schematic view of two first embodiment VOAs of the present invention;

[0015] FIG. 3 is an end sectional view 3-3 of FIG. 2;

[0016] FIG. 4 is a lateral sectional view 4-4 of FIG. 2;

[0017] FIGS. 5A and 5B are sectional views 5A-5A and 5B-5B, respectively, of FIG. 2 illustrating alternative embodiments for VOA electrodes;

[0018] FIG. 6 is a sectional side view, indicated as view 6-6 of top schematic view FIG. 2, showing one VOA and power meter of a second embodiment array of VOAs and power meters of the present invention;

[0019] FIG. 7 is a top view of one of the second embodiment VOAs and corresponding power meter of an array of VOAs and power meters of the present invention;

[0020] FIG. 8 is a sectional side end view 8-8 of FIG. 7;

[0021] FIG. 9 is a sectional side view showing some operational features of the second embodiment VOA and power meter of the present invention;

[0022] FIG. 10 is a sectional side view, indicated as view 10-10 of top schematic view FIG. 3, showing one VOA and power meter of a third embodiment array of VOAs and power meters of the present invention;

[0023] FIG. 11 is a top view of one of the third embodiment VOAs and corresponding power meter of an array of VOAs and power meters of the present invention;

[0024] FIG. 12A is a sectional side end view 12-12 of FIG. 11;

[0025] FIG. 12B is a sectional side end view 12-12 of an alternative embodiment of FIG. 11;

[0026] FIGS. 13A and 13B are planar sectional views 13-13 of FIG. 12A showing a first electrode embodiment and a second embodiment, respectively.

[0027] FIG. 14A is a cross-sectional view of a first domain of materials used in a computer simulation of a VOA;

[0028] FIG. 14B is a graph showing the results of calculations using the domain of FIG. 14A, illustrating the loss of optical power as a function of the cladding height and the refractive index of the drain layer;

[0029] FIG. 15A is a cross-sectional view of a second domain of materials used in a computer simulation of a VOA;

[0030] FIG. 15B is a graph showing the results of calculations using the domain of FIG. 15B, illustrating the attenuation in a waveguide as a function of the cladding height and refractive index;

[0031] FIG. 16 is a graph showing the calculated attenuation in a VOA having a periodic electrode;

[0032] FIG. 17 shows the dimensions for one embodiment VOA for 1550 μm light;

[0033] FIG. 18 shows the effect of the R.I. of the drain layer on attenuation for two values of drain layer refractive index; and

[0034] FIGS. 19A – 19K shows the manufacturing steps for producing a VOA array **100**.

[0035] Reference symbols are used in the Figures to indicate certain components, aspects or features shown therein, with reference symbols common to more than one Figure indicating like components, aspects or features shown therein.

DETAILED DESCRIPTION OF THE INVENTION

[0036] The present invention is directed to a VOA that overcomes the problems associated with currently available VOAs. For example, VOAs provided in accordance with the present invention are faster than current VOAs, can be manufactured in closely packed arrays, and are readily amenable to monitoring of the attenuation. They are thus readily usable in WDM networks. More specifically, a VOA according to the present invention provides attenuation by controlling the leakage of light from the core of a waveguide into an optically-coupled layer. This layer is sometimes referred to herein at a "drain layer." By selection of the optical properties of the drain layer, attenuation is enhanced and the leaked light is confined to the layer, facilitating monitoring of light attenuated from an input signal.

[0037] FIG. 1 is a schematic of an array of VOAs **100** and an array of intensity monitors, or power meters **18** of the present invention as used in a gain equalizer **10** of a WDM network. In addition to VOA array **100** and intensity meter array **18**, gain equalizer **10** includes a demultiplexer (DMUX) **15**, a multiplexer (MUX) **25**, and a controller **33**. Gain equalizer **10** accepts a WDM signal **17'** from a source **11** provided by a fiber **13**, and separately adjusts the intensity of each WDM signal to produce an equalized signal **21'** that is then transmitted through a fiber **27** to a WDM signal receiver **29**.

[0038] Using WDM each signal, such as signal **17'** and signal **21'**, contains 2 or more individual signals or channels. The number of channels is indicated herein as "n," where n is a number equal to or greater than 2. Individual ones of signal **17'** are denoted, in general, as signal **17**, as one of signals **17(1)**, **17(2)**, ... , **17(n)**, or in reference to one of signal **17(m)**, where m is a generalized index. Individual ones of signal **21'** are denoted by a similar reference to signal **21**, one of signals **21(1)**, **21(2)**, ... , **21(n)**, or by reference to index m, as in signal **21(m)**.

[0039] Gain equalizer **10** adjusts the intensity of signal **17'** to form signal **21'** as follows.

DMUX **15** accepts a WDM signal **17'** and separates the WDM signal into the **n** separate signals **17**. VOA array **100** includes n separate VOAs corresponding to each WDM channel, specifically VOA **101(1)**, VOA **101(2)**, ... , VOA **101(n)**. Individual ones of the array of VOAs are referred to herein as VOA **101**, or by a number other than n, for example the mth VOA is referred to as VOA **101(m)**.

[0040] As described subsequently, VOA **101** accepts signal **17** and produces two optical outputs: equalized signal **21** and a monitor signal **23**. Using the numbering convention introduced above, the n monitor signals **23** are referred to as one of monitor signal **23(1)**, **23(2)**, ... , **23(n)**. VOA array **100** also includes an array of intensity monitors **18** that includes n separate intensity monitors **19(1)**, **19(2)**, ... , **19(n)**, or in general, intensity monitor **19**. As described subsequently, each intensity monitor **19** accepts a monitor signal **23** and produces an electrical signal **31** that is proportional to the intensity of the monitor signal. Controller **33** accepts electrical signal **31** from each of the n channels, calculates a correction to be applied to the attenuation of the corresponding signal **17** within VOA **101**, and provides a correction signal **35** to that VOA. In one embodiment, each channel is attenuated independently from one another according to the monitored signal of that channel. In another embodiment, one or more channels are attenuated using information from other channels. Thus for example, one of the channels provides known intensity levels to calibrate VOA array **100**. MUX **25** then recombines the **n** equalized signals **23** into equalized WDM signal **21'**. Multiplexers and demultiplexers are known in the art, and can include, for example, an array waveguide grating (AWG) or thin-film filters.

[0041] A schematic of the VOA array **100** of the present invention is presented in FIGS. 2, 3, and 4, where FIG. 2 is a top schematic view of two first embodiment VOAs **100** of the present invention formed on a substrate **201**, FIG. 3 is an end sectional view 3-3 of FIG. 2, and FIG. 4 is a lateral sectional view 4-4 of FIG. 2. FIGS. 2, 3, and 4 are illustrative and as such highlight some aspects of the present invention. As will be apparent from the discussion of this and other embodiment, there are many materials and configuration that are within the scope of the present invention, which is not limited by the embodiments presented herein.

[0042] FIG. 2 shows two representative and adjacent VOAs as VOA **101(m)** and **101(m+1)**. Each VOA **101** extends from an input **202** that is optically coupled to DMUX **15** for accepting

signal **17** and to an output **204** that is coupled to MUX **25** for providing equalized signal **21**. As shown in FIGS. 3 and 4, each VOA **101** includes a drain layer **213** and a waveguide **203** that includes a core **205** and a surrounding cladding **211**. The optical properties of core **205**, cladding **211**, and drain layer **213** are selected such that the attenuation of light between input **202** and output **204** can be controlled, as described subsequently.

[0043] The attenuation of light through core **205** is achieved by propagating light through the core while modifying the refractive index (R.I.) of cladding **211** between core **205** and drain layer **213**. The light attenuated from core **205** is coupled to drain layer **213** according to the modified R.I. of cladding **211**. A preferred, refractive index modifiable material to form all or part of cladding **211** is an EO material. As is known in the art, these materials have a R.I. that varies with the electric field within the material. The electro-optic effect is intrinsically very fast, resulting from atomic level changes to the EO material. These changes can occur with speeds on the order of several nanoseconds. The operational speed of VOA **101** can be as fast as from about 1 to about 500 nanoseconds.

[0044] In the present invention, electrodes are provided in the vicinity of an EO material of the waveguide cladding to produce a change in R.I. according to the voltage difference applied to electrodes (shown in FIGS 5A and 5B) that are located on opposite sides of, or near, cladding **211** between core **205** and drain layer **213**. It is preferred that with little or no applied voltage to the electrodes of VOA **101**, waveguide **203** is a low-loss waveguide, and that when a voltage is applied to the electrodes of the VOA that the losses through the waveguide increase, with a substantial amount of the light attenuated from the VOA being directed into drain layer **213**.

[0045] While the selection of optical properties is discussed subsequently, it is preferred, though not necessary, that the material properties and dimensions are selected so that (1) when no voltage difference is applied across the electrodes of the VOA, cladding **211** has a uniform R.I. that efficiently permits transmission of light through the VOA, and (2) when a voltage difference is applied across the electrodes of the VOA, an electric field is established that affects the R.I. of cladding **209** between core **205** and drain layer **213**, coupling light from the core into the drain layer. The fraction of light entering input **202** that emerges from output **204** can be controlled according to the voltage difference applied to the electrodes. The control of the light signal

through VOA **201** is thus achieved by modifying the R.I. of electro-optic layer **209** by the application of an electric field to the layer, for example, according to a voltage difference applied across layer **209**, as discussed subsequently. Since the light attenuated from VOA **201** is coupled into drain layer **213**, the light attenuated from the VOA is not scattered back towards core **205**, and can be conveniently sampled from the layer and can be used to control the VOA, as described subsequently.

[0046] More specifically, cladding **211** includes a first cladding **207** and a second cladding **209**. The R.I. of second cladding **209** is adjustable, as described below, while the refractive indices of core **205**, first cladding **207**, and drain layer **213** are relatively constant, or much less variable than the R.I. of the second cladding. Alternatively, cladding **207** and **209** can both be formed from an EO material. As in known in the art, the R.I. of the EO material of cladding **209** can be modified continuously and controllably. The control of R.I. allows the inventive VOA to controllably attenuate the light between input **202** and output **204**.

[0047] It is preferred that core **205** and drain layer **213** have the same R.I., and that cladding **207** has a lower R.I. Cladding **209** is formed from an EO material that, by the application of a suitable electric field, has an R.I. that can be varied between the R.I. of core **205** and drain layer **213** and the R.I. of cladding **207**. It is also preferred that, in the absence of an electric field (when the electrodes are "unpowered"), the refractive indices of cladding **209** and cladding **207** are the same, resulting in an attenuation across VOA **101** that is small, for example on the order of 0 dB, and that, in the presence of an electric field (when the electrodes are "powered"), the R.I. of cladding **209** is equal to the R.I. of core **205** and drain layer **213**, resulting in an attenuation across the VOA that is larger, for example, as much as 15 dB/cm.

[0048] Waveguide **203** thus has a small attenuation when VOA **101** is unpowered, and an increasing attenuation with increased power input. The portion of light from input **202** that does not reach output **204** is referred to herein as the "leaked" light (the light has leaked from waveguide **203**). The leaked light preferentially propagates through drain layer **213** and emerges near output **204** as monitor signal **23**. Although signal **23** is shown propagating in the direction of waveguide **203**, it is understood that some of the light may propagate away from the waveguide, shown schematically as light ray **23'**. Monitor signal **23** is thus some fraction of the

light attenuated from signal **17**.

[0049] Two embodiments of cladding **211** and electrodes for inducing changes in the R.I. of EO material of cladding **211** are illustrated in FIGS. 5A and 5B as sectional views 5A-5A and 5B-5B, respectively, of FIG. 2. In the embodiments of FIGS. 5A and 5B, core **205** and drain layer **213** optical polymers having a R.I. of 1.567, and cladding **207** is an optical polymer having a R.I. of 1.563. Cladding **209** is an EO material having a R.I. of 1.563 in the absence of an electric field and a R.I. of 1.567 at some maximum voltage difference between the electrodes.

[0050] FIG. 5A shows a VOA **101'** having an electrode **501a** on top of drain layer **213** and an electrode **501b** between substrate **201** and cladding **207**. Electrodes **501a** and **501b** extend the length of VOA **101'**, and cladding **209** is confined in the region between core **205** and drain layer **213**. The application of a voltage difference between electrodes **501a** and **501b** produces an electric field within the EO material of second cladding **209** that increases the R.I. of the second cladding.

[0051] FIG. 5B shows a VOA **101"** having a first cladding **207'** that extends to the top of core **205** and a second cladding **209'** that extends from the core and first cladding to drain layer **213**. Second cladding **209'** has a first electrode **503a** and a second electrode **503b** embedded within the second cladding. Electrodes **503a** and **503b** extend the length of VOA **101"**, and cladding **209** is confined in the region between core **205** and drain layer **213**. The gap between electrodes **503a** and **503b** produces an electric field, and thus a change in R.I. of the EO material of cladding **209**, within region **507**. In addition, the gap between electrodes **503a** and **503b** form an aperture between core **205** and drain layer **213** to allow light attenuated from the core propagate into the layer. It is thus seen that it is the combination of the EO material and the placement of the electrodes that modifies the R.I. of the cladding in the region between core **205** and drain layer **213** and optically couples the core and drain layer.

[0052] Computer simulations of simplified VOA structures illustrate the effect of R.I. and dimensions of the VOA on attenuation. These results are presented in FIGS. 14A-15B as the loss or attenuation of optical power, in dB/cm of waveguide length, as a function of various design parameters. FIGS. 14A and 15A are cross-sectional views, similar to view 3-3 of FIG. 2, of two simulation computational domains, and FIGS. 14B and 15B are corresponding graphs

showing the results of simulations of the propagation of 1.550 μm light. FIG. 14A shows a first domain **1400** having a core **1401**, a cladding **1403**, and a drain layer **1405**. For the results presented in FIG. 14B, core **1401** has a R.I. of 1.567 and has a square cross section of **s** = 7 μm on a side and is surrounded by cladding **1403** having a R.I. of 1.563. Cladding **1403** extends a height **d** from core **1401** to drain layer **1405**. The total height and width of the simulation is **A** = 50 μm on a side centered about core **1401**.

[0053] FIG. 14B shows the loss of optical power as a function of the height **d** of cladding **1403** and the R.I. of drain layer **1405**. The entire cladding **1403** has the same R.I., and thus these calculations represent the loss from an unpowered VOA. For each value of **d** presented in FIG. 14B, the loss of optical power is a minimum when the R.I. of drain layer **1405** is the same as the R.I. of cladding **1403** – that is drain layer **1405** acts as additional cladding when the R.I. of the drain layer matches that of the cladding. In addition, for each value of **d**, the loss is a maximum when the R.I. of drain layer **1405** is the same as the R.I. of core **1401** due, in part, to optical coupling of the core and drain layer. Also, a reduction in **d** for any value of drain layer **1405** R.I. is a reduction in cladding thickness that increases the loss of optical power.

[0054] FIG. 15A shows a computational domain **1500** having a core **1501**, a lower cladding **1503**, an upper **1505** having embedded electrodes **1509a** and **1509b**, and a drain layer **1507**. For the results presented in FIG. 15B, core **1501** has a R.I. of 1.567 and has a square cross section of **s** = 7 μm on a side and is surrounded on one side by lower cladding **1503** having a R.I. of 1.563 and on another side by upper cladding **1505**. Upper cladding **1505** has a variable height **d** and variable R.I. Electrodes **1509a** and **1509b** have a separation of **b** of 20 μm and are located a height **t** = 4 μm from the interface between lower cladding **1503** and upper cladding **1505**. The application of a voltage difference between electrodes **1509a** and **1509b** is simulated by modifying the R.I. region **1511**. The total height and width of the simulation is **A** = 50 μm on a side.

[0055] FIG. 15B shows that the attenuation depends on **d** and on the R.I. of cladding **1505**, with an increased attenuation for smaller values of **d** and at values of the R.I. of the cladding approaching the R.I. of core **1501**.

[0056] The results of FIGS. 14B and 15B indicate that there is a trade-off in loss and attenuation

with several design parameters. Specifically, the results show that the coupling of light out of an unpowered VOA **101** is greatest when the core and drain layer have the same R.I. and when the thickness of the cladding between the core and drain layer is smallest, and that by changing the refractive index of the cladding that the attenuation can be varied. FIG. 17 shows the dimensions for one embodiment for a VOA **1701** of the present invention having core **1705**, a cladding **1711** including a first cladding **1707** and a second cladding **1709**, and a drain layer **1713**. In addition, VOA **1701** has electrodes disposed about second cladding **1709** that are not shown, but which were discussed with reference to FIGS. 5A and 5B, and are discussed in detail subsequently. In the preferred embodiment, core **1705** has a R.I. of 1.567 and has a square cross section of **s** = 7 μm on a side and is surrounded on the bottom and sides by first cladding **1707** and on top by second cladding **1709**. First cladding **1707** has a R.I. of 1.563 and extends a distance **Z** below core **1705**, where **Z** is from 5 μm to 20 μm, preferably about 15 μm. Second cladding **1709** extends a distance **Y** from core **1705** to layer **1713**, and includes an EO material with a R.I. that can be varied from 1.563 to 1.567 as the voltage difference across the electrodes is increased from zero to some maximum value. The value of **Y** is from 5 μm to 20 μm, preferably about 8 μm. Layer **1713** preferably has the same R.I. as core **1705**, and has a height **T** that is from 1 μm to 10 μm, or more preferably from 3 μm to 5 μm. VOA **1701** has a width **W** that is 30 μm or larger, preferably about 250 μm.

[0057] FIG. 18 is a graph which shows the effect of the R.I. of layer **1713** on attenuation, where the attenuation as a function of the R.I. of cladding **1709** is shown in curve **1801** for a R.I. of layer **1713** having the same value as the R.I. of core **1705**, and in curve **1802** for a R.I. of layer **1713** having the same value as the R.I. of cladding **1707**. FIG. 18 illustrates that a waveguide having equal layer **1713** and core **1705** refractive indices has a higher attenuation at the same R.I. of cladding **1709**. The R.I. of layer **1713** is thus effective at improving the performance of the VOA.

[0058] A second embodiment VOA **601** and a corresponding power meter **19** is shown in FIGS. 6-8, where FIG. 6 is a sectional side view 6-6 of FIG. 2, FIG. 7 is a top view, and FIG. 8 is a sectional side end view 8-8 of FIG. 7. Each VOA **601** has an input **602** to accept a light input **17**, an output **604** to provide a signal **21**, and a monitor output **606** to provide a monitor signal **23**. VOA **601** includes a waveguide core **605** from the input to the output that is surrounded by a

cladding **611**, a drain layer **613** on top of cladding **611**, and a first electrode **621** between cladding **611** and substrate **201** and a second electrode **623** on top of a layer **613** that includes the monitor output. Cladding **611** includes a first cladding **607** and a second, EO cladding **609**. Specifically, EO cladding **609** is formed from an EO material, and first cladding **607**, core **605**, and layer **613** are formed from materials that are not EO. Input **602** and output **604** correspond to the ends of core **605**, where light is coupled into the core and out of the core, respectively, preferably by optical fibers (not shown).

[0059] The materials of core **605**, cladding **611**, and layer **613** are optically transparent materials for wavelengths of the WDM signals. The materials of substrate **201** can be, but are not required to be, optically transparent at the WDM wavelengths. The material optical properties and dimensions, as well as the spacing and placement of electrodes **621** and **623**, are selected to controllably pass, attenuate, or block light traveling across VOA **601** from input **602** and towards output **604**, as indicated by the arrow within core **605** in FIG. 6, according to the electro-optically controllable R.I. of EO cladding **609**, as follows. When EO cladding **609** has a R.I. equal to the R.I. of core **605**, the dimensions and materials of VOA **601** are such that the core and cladding **611** are a high-loss waveguide between input **602** and output **604**. When EO cladding **609** has a R.I. equal to that of cladding **607**, the dimensions and materials of VOA **601** are such that core **605** and cladding **611** are a low-loss waveguide of light entering core **605**. At R.I. values between that of core **605** and cladding **607**, a controllable fraction of the light is transmitted across the variable optical attenuator **601**.

[0060] Core **605** is preferred to have a cross-sectional shape that is rectangular or square. As shown in the preferred embodiment of FIG. 8, core **605** has a square cross-section with each side having a length **X**. Cladding **607** has a thickness **Z**, and EO cladding **609** has a thickness **Y**. Layer **613** has a thickness **T**. VOA **601** has a width **W** that is preferably approximately equal to the height of the VOA ($\mathbf{W} \approx \mathbf{X} + \mathbf{Y} + \mathbf{Z}$). Core **605** has a refractive index of R.I. (core), layer **613** has a refractive index R.I. (layer), cladding **607** has a refractive index of R.I. (cladding), and EO cladding **609** is an EO material with a variable refractive index R.I. (E-O) dependent on the applied electric field. The application of voltage difference of ΔV between electrodes **621** and **623** establishes an electric field of approximately $-\Delta V/S$, where S is the spacing between electrodes **621** and **623** ($S = \mathbf{X} + \mathbf{Y} + \mathbf{Z} + \mathbf{T}$) to which the R.I. of EO cladding **609** is responsive.

[0061] In one preferred embodiment, core **601** has a R.I. of 1.567 and has a square cross section of **X** = 7 μm on a side and is surrounded on the bottom and sides by first cladding **607** and on top by EO cladding **609**. First cladding **607** has a R.I. of 1.563 that extends a distance **Z** below core **605**, where **Z** is from 5 μm to 20 μm, preferably about 15 μm. The EO cladding **609** extends a distance **Y** from core **605** to layer **613**, and includes an EO material with a R.I. that can be varied from 1.563 to 1.567 as the voltage difference across the electrodes is increased from zero to a predetermined value. The value of **Y** is from 5 μm to 20 μm, preferably about 8 μm. Layer **613** preferably has the same R.I. as core **605**, and has a height **T** that is from 1 μm to 10 μm, or more preferably from 3 μm to 5 μm. VOA **601** has a width **W** that is 30 μm or larger, preferably about 250 μm.

[0062] Preferred materials for core **605** and layer **613** include optical polymers, including but not limited to low loss optical epoxies. Preferred materials for cladding **607** are the same as for core **605** with dopants added to modify the cladding R.I. to be slightly lower than that of the core, for example 2% to 10% of another epoxy with a lower R.I. Preferred materials for substrate **601** include, but are not limited to materials typically used in manufacturing of substrate wafers, such as silicon. Preferred materials for EO cladding **609** include materials that have R.I. ranges between those of the core and cladding and have electro-optic coefficients that allow their use with reasonable applied voltages, including but not limited to mixtures of poly-carbonate and a chromophore. Preferred materials for electrodes **621** and **623** are metals that can be deposited using methods compatible with semiconductor manufacturing techniques and with the layers of VOA **601**, for example, tungsten, titanium, and copper.

[0063] In one embodiment, core **605**, layer **613**, and cladding **607** are formed from one type of optical polymer, and EO cladding **609** is formed from the same or a similar polymer with additives, including but not limited to poly-carbonate and a chromophore, that make the polymer electro-optic. The operation of VOA **101** with these materials requires an electric field on the order of about 1 to about 100 V/μm for appropriate modification of the R.I. Preferred electrode spacing to produce his electric field are from about 5 to about 20 μm, with a preferred voltage difference of about 10 to about 100 volts.

[0064] FIG. 9 is a sectional side view showing some operational features of the second

embodiment VOA **601** and corresponding power meter **19** of the present invention, depicting rays **A**, **B**, **C**, and **D** which illustrate the propagation or deflection of light through the VOA. As described previously, the application of a voltage difference ΔV between electrodes **621** and **623** modifies the R.I. of EO cladding **609** to the value away from that of cladding **607** and towards the R.I. of core **605** and layer **613**. Under these conditions a fraction of the light propagating through core **605** is coupled out of the waveguide according to the difference in value of the refractive indices. Light as ray **A** is provided to VOA **601** at input **202**. With $\Delta V = 0$ volts, the R.I. of EO cladding **609** is the same as that of cladding **607**, and the majority of input light propagates within in core **605** to output **204**, as indicated schematically as the output of light by ray **D**.

[0065] When the R.I. of EO cladding **609** is the same as that of core **605**, light "leaks" from the core, through EO cladding **609**, and into layer **613**. As indicated by rays **B** and **C**, light first propagates into that portion of cladding **609** having the electro-optically modified R.I. A layer **625** that is coplanar with layer **613**, has a R.I. different from layer **613**, and has an angled surface **629** having a layer of vaporized gold, for example, directs light of ray **C** 90 degrees through monitor output **606** as monitor signal **23** towards intensity monitor **19**. Intensity monitor **19** responds to the intensity of light in monitor signal **23** as electrical signal **31** which is provide to controller **33**. Controller **33** in turn provides voltages to one or both of electrodes **621** and **623**, thereby controlling the amount of attenuation of VOA **101**. Controller **33** can supply different voltages to different ones of VOAs **101** to control the gain of individual WDM signal channels.

[0066] In one embodiment, power meter **19** includes a Indium Gallium Arsenide (InGaAs) PIN photodiodes mounted to accept signal **23**. Power meter **19** can be mounted, for example, using flip-chip bonding technology with either gold or gold-tin bumps.

[0067] A third embodiment VOA **1001** as a corresponding power meter **19** is shown in FIGS. 10-13, where FIG. 10 is a sectional side view 10-10 of FIG. 2, FIG. 11 is a top view, FIG. 12A is a sectional side end view 12-12 of FIG. 11, and FIG. 13A is a planar sectional view 13-13 of FIG. 12A showing the electrode configuration. Each VOA **1001** has an input **1002** for accepting a light signal **17**, an output **1004** to provide a signal **21**, and a monitor output **1006** for providing a monitor signal **23**. VOA **1001** includes core **605**, cladding **607** and EO cladding **609**, layer **613**

and layer **625**. One difference in between the second embodiment VOA **601** and the third embodiment VOA **1001**, is in the placement of the electrodes. Specifically, VOA **1001** has a first electrode **1021** and second electrode **1023** within the EO material of cladding **609**. As is best shown in FIGS. 12A and 13A, electrodes **1021** and **1023** present mutually opposing edges **1022** and **1024**, respectively. When electrodes **1021** and **1023** have an imposed voltage difference, an electric field is established within EO cladding **609** between edges **1022** and **1024**, which modifies the R.I. of the cladding between core **605** and layer **612**. Edges **1022** and **1024** also form an aperture between core **605** and layer **613**, permitting light leaked from the core to propagate through EO cladding **609** to layer **613**.

[0068] It is important that the material between edges **1022** and **1024** include the EO material through which light can propagate into layer **613**. FIG. 12B is a sectional side end view 12-12 of an alternative embodiment VOA **1001'** of FIG. 11, where electrodes **1021** and **1023** are formed on a material **1205**, and where EO cladding **609** fills the space between edges **1022** and **1024** and above electrodes **1021** and **1023**. In addition, cladding **607** of VOA **1001** is formed from an under cladding **1203** between core **605** and substrate **201**, and a side cladding **1201**. It is preferred that the materials of claddings **1201** and **1203** are the same as cladding **1203**. Having an under cladding **1203** that protrudes only to the bottom of core **605** may be performed to facilitate fabrication of the VOA, as discussed in reference to FIGS. 19A – 19K.

[0069] An alternative electrode arrangement, referred to herein as periodic electrodes, is presented in FIG. 13B, which is a planar sectional view 13-13 of FIG. 12A. Two alternative electrodes, electrode **1021'** and **1023'** present mutually opposing edges **1022'** and **1023'**, respectively across EO cladding **609**. Each edge **1022'** and **1024'** alternates between a first edge **1022a** and **1024a** having a width **a**, a second edge **1022b** and **1024b** having a width **b**, and an edge **1022c** and **1024c** between the "a" and "b" edges. The "a" and "b" edges are aligned such that the spacing between electrodes **1021'** and **1023'** is periodic along the length of the VOA, with a fraction a/(a+b) having a spacing of **S1** and a fraction b/(a+b) having a spacing of **S2**. The alternating spacing results in an alternating R.I. in EO cladding **609** when there is a voltage difference between electrodes **1021'** and **1023'**.

[0070] The attenuation due to R.I. changes resulting from an applied voltage difference was

simulated by varying the R.I. within the space between electrodes. The attenuation of a VOA having electrodes according to FIG. 13B varies with **S1**, **S2**, **a**, and **b** of periodic electrodes **1022'** and **1024'**. In particular, the response of the attenuation with changes in the R.I. changes, permitting design control over the sensitivity of the change in attenuation with voltage difference. FIG. 16 is a graph showing the calculated attenuation, in dB/cm, of a VOA **1001'**, where **S1** = **20** μm, **S2** = 50 μm, a and b varied simultaneously from 275 μm to 525 μm, in increments of 50 μm. The curve marked "b = 0 μm" represents a pair of straight electrodes. Increasing the value of b increases the attenuation for most values of b and cladding R.I. A value of b of 425 μm produces the largest attenuation for a given R.I. change.

[0071] There are several methods for manufacturing the VOA of the present invention. FIGS. 19A - 19K presents a method for manufacturing VOA array **1001'** using techniques that are well known in the field of microelectronics and fiber optic manufacturing. FIGS. 19A - 19F show the formation of core **605** and cladding **1201** and **1203**. As shown in FIG. 19A, substrate **201** formed from a silicon wafer is coated with the material of waveguide under cladding **1203**.

[0072] Coating is performed by the steps of spin coating or meniscus coating. Cladding **1203** may be, but is not limited to, a UV-curable epoxy. Core **605** is formed from a material having a lower R.I. than the materials of claddings **1201** and **1203**, and may be, but is not limited to, another UV-curable epoxy. As shown in FIG. 19B, core **605** is formed by coating the core material (for example by spin coating or meniscus coating), exposing the coated core material to UV light in a pattern corresponding to cure the material where the core is required (UV patterning and curing), and etching the uncured core material by developing solution. The cladding is then finished from a cladding material **1901**, which is, like the material of cladding **1203** is preferably, but not limited to a UV-curably epoxy, but which has a R.I. higher than that of core **605**, by coating the cladding material over the core (for example by spin coating or meniscus coating) and curing the cladding material by exposing it to UV light (FIG. 19C), polishing the cladding material **1901**, for example by chemical polishing or mechanical polishing to the top of core **605**, as shown in FIG. 19D, thus forming cladding 1201. Material **1903** of cladding **1201** is then deposited over cladding **1201** and core **605** (FIG. 19E) for example by spin coating or meniscus coating, and trenches **1905** are formed through material **1903** and over core **605**, as shown in FIG. 19F by plasma etching.

[0073] After core **605**, under cladding **1203**, and side cladding **1201** formed, the electrodes are provided next. As shown in FIG. 19G, metal **1907** is evaporated on the exposed portions of cladding **1201** and core **605**. Evaporation can be performed by sputtering or vacuum-evaporation. Choices for metal **1907** include, but are not limited to titanium, copper, or gold. Resist **1909** is then patterned over metal **1907** in the locations where electrodes are to be located by coating and UV patterning the resist, as shown in FIG. 19H. Exposed metal **1907** is etched by acid preparation, and then etching resist **1909** is removed by photoresist strippers, as shown in FIG. 19I, resulting in electrodes **1021** and **1023** being in place over material **1205** and trench **1905** uncoated.

[0074] Next, the cladding of an electro-optic material is deposited and formed, as shown in FIG. 19J. Materials for cladding **609** include, but are not limited to a polycarbonate and a chromophore. As shown in FIG. 19K, drain layer **613**, which is preferably a UV-curable epoxy with a R.I. similar to core **605** is coated next on top of EO cladding **609**. After that, EO cladding **609** is poled with an electric field by application of DC voltage between electrodes **1201** and **1203**, for example, at 10 V/um at 150 °C for one hour. The remaining steps, not presented here, provide vias to electrodes **1201** and **1203** if needed, followed by dicing the chip, the mounting of power meters **19**, for example by flip-chip bonding technology with either gold or gold-tin bumps, and packaging the finished VOA **1001'**.

[0075] The embodiments described above are illustrative of the present invention and are not intended to limit the scope of the invention to the particular embodiments described. Accordingly, while one or more embodiments of the invention have been illustrated and described, it will be appreciated that various changes can be made therein without departing from the spirit or essential characteristics thereof. For example, other materials, electrode geometries, or control schemes may be used with the present invention. Accordingly, the disclosures and descriptions herein are intended to be illustrative, but not limiting, of the scope of the invention, which is set forth in the following claims.